# Graphene, the Idea, the Material and the Future

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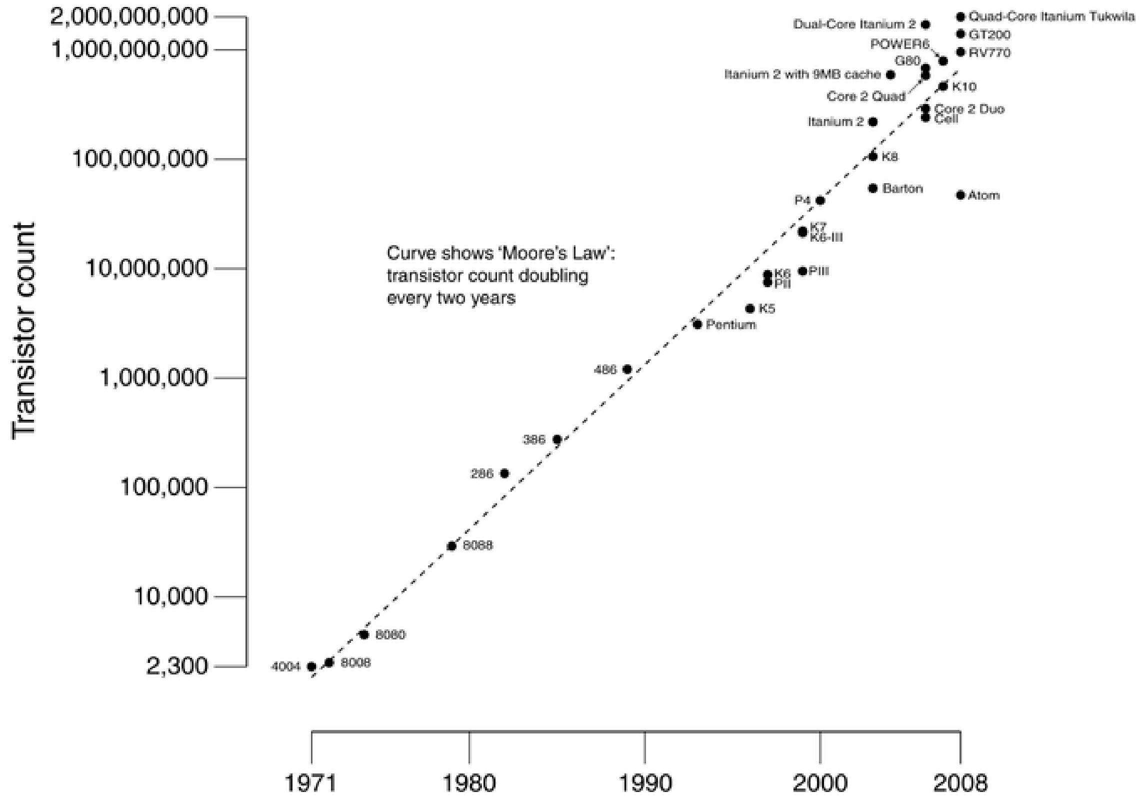
PITP Lecture on Quantum Phenomena, January 12, 2011

## Graphene superlatives (from Andre Geim)

- Thinnest imaginable material
- Strongest material "ever measured" (theoretical limit)
- Stiffest known material (stiffer than diamond)
- Most stretchable crystal (up to 20 percent)
- Record thermal conductivity (outperforming diamond)
- Highest current density at room temperature (million times higher than Copper)
- Highest intrinsic mobility (100 times more than Silicon)
- Conducts electricity even with no electrons.
- Lightest charge carriers (massless).
- Longest mean free path at room temperature (microns)
- Most impermeable (even Helium atoms can't squeeze through).

**Moore's Law (1965):** The number of transistors that can be placed inexpensively on an integrated circuit has doubled approximately every two years. The trend has continued for more than half a century and is not expected to **stop** until 2015 or later.



Transistor count
2,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
2,300
Curve shows 'Moore's Law':
transistor count doubling
every two years
Quad-Core Itanium Tukwila
Dual-Core Itanium 2
GT200
POWER6
RV770
G80
Itanium 2 with 9MB cache
K10
Core 2 Quad
Core 2 Duo
Cell
Itanium 2
K8
Barton
Atom
P4
K7
K6-III
K6
PII
PIII
K5
Pentium
486
386
286
8088
8080
8008
4004
1971
1980
1990
2000
2008

*Will graphene extend Moore's law beyond Silicon?*

IBM

# Made in IBM Labs: IBM Scientists Demonstrate World's Fastest Graphene Transistor

**Holds Promise for Improving Performance of Transistors**

- Press release
- Related XML feeds

- Contact(s) information

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**YORKTOWN HEIGHTS, N.Y. - 05 Feb 2010:** In a just-published paper in the magazine Science, IBM (NYSE: IBM) researchers demonstrated a radio-frequency graphene transistor with the highest cut-off frequency achieved so far for any graphene device - 100 billion cycles/second (100 GigaHertz).

http://www.newscom.com/cgi-bin/prnh/20100205/NY50316

This accomplishment is a key milestone for the Carbon Electronics for RF Applications (CERA) program funded by DARPA, in an effort to develop next-generation communication devices.

The high frequency record was achieved using wafer-scale, epitaxially grown graphene using processing technology compatible to that used in advanced silicon device fabrication.

"A key advantage of graphene lies in the very high speeds in which electrons propagate, which is essential for achieving high-speed, high-performance next generation transistors," said Dr. T.C. Chen, vice president, Science and Technology, IBM Research. "The breakthrough we are announcing demonstrates clearly that graphene can be utilized to produce high performance devices and integrated circuits."

Graphene is a single atom-thick layer of carbon atoms bonded in a hexagonal honeycomb-like arrangement. This two-dimensional form of carbon has unique electrical, optical, mechanical and thermal properties and its technological applications are being explored intensely.

Uniform and high-quality graphene wafers were synthesized by thermal decomposition of a silicon carbide (SiC) substrate. The graphene transistor itself utilized a metal top-gate architecture and a novel gate insulator stack involving a polymer and a high dielectric constant oxide. The gate length was modest, 240 nanometers, leaving plenty of space for further optimization of its performance by scaling down the gate length.

It is noteworthy that the frequency performance of the graphene device already exceeds the cut-off frequency of state-of-the-art silicon transistors of the same gate length (~ 40 GigaHertz). Similar performance was obtained from devices based on graphene obtained from natural graphite, proving that high performance can be obtained from graphene of different origins. Previously, the team had demonstrated graphene transistors with a cut-off frequency of 26 GigaHertz using graphene flakes extracted from natural graphite.

## Contact(s) information

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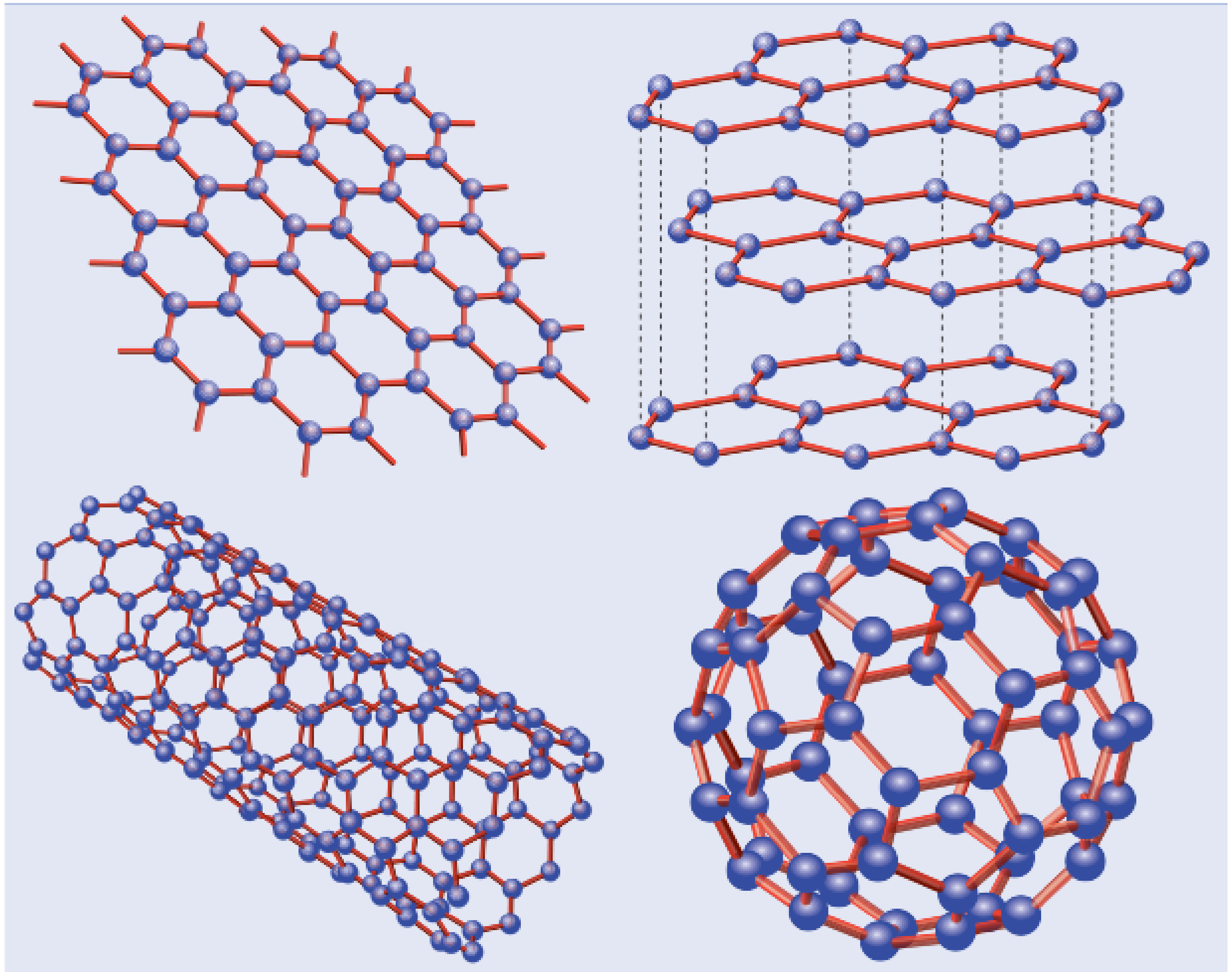
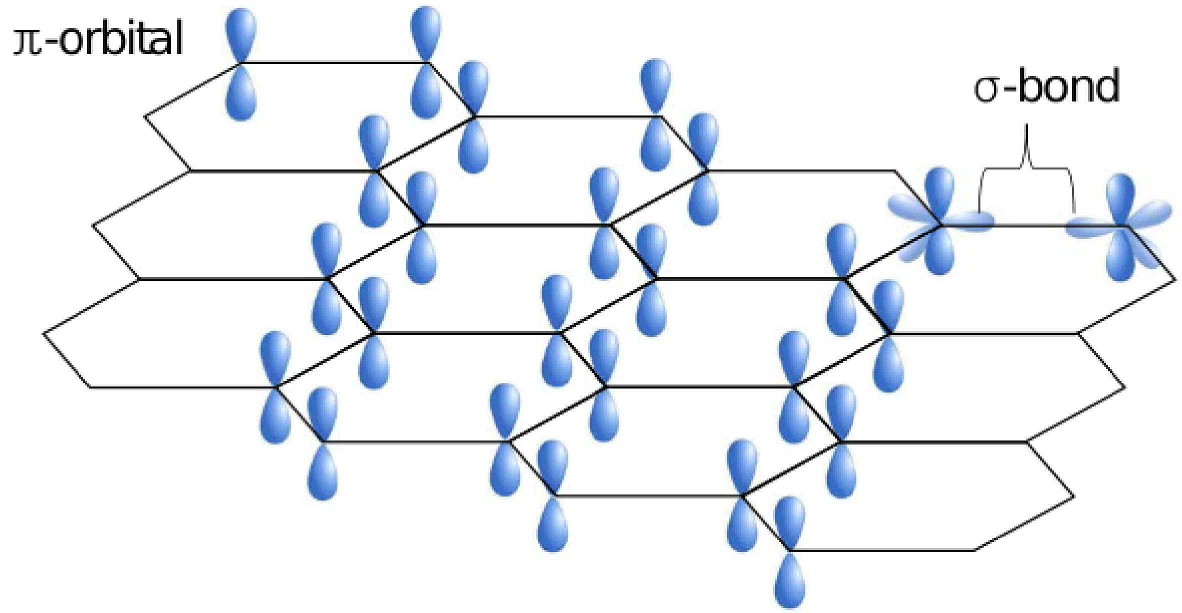
## Graphene is a 2-dimensional array of carbon atoms with a hexagonal lattice structure:

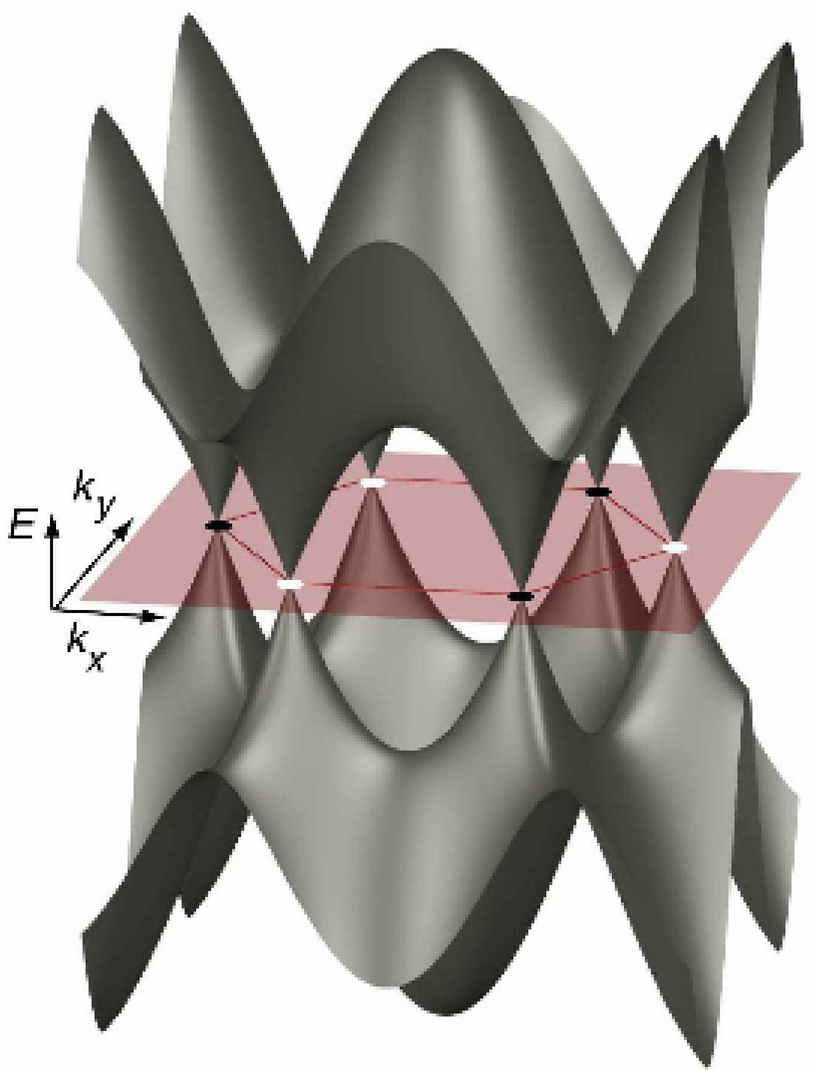


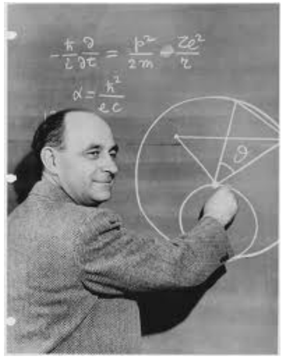



A carbon atom has four valence electrons. Three of these electrons form strong covalent $\sigma$-bonds with neighboring atoms. The fourth, $\pi$-orbital is un-paired.

L. Pauling 1972 "*The Nature of the Chemical Bond*"

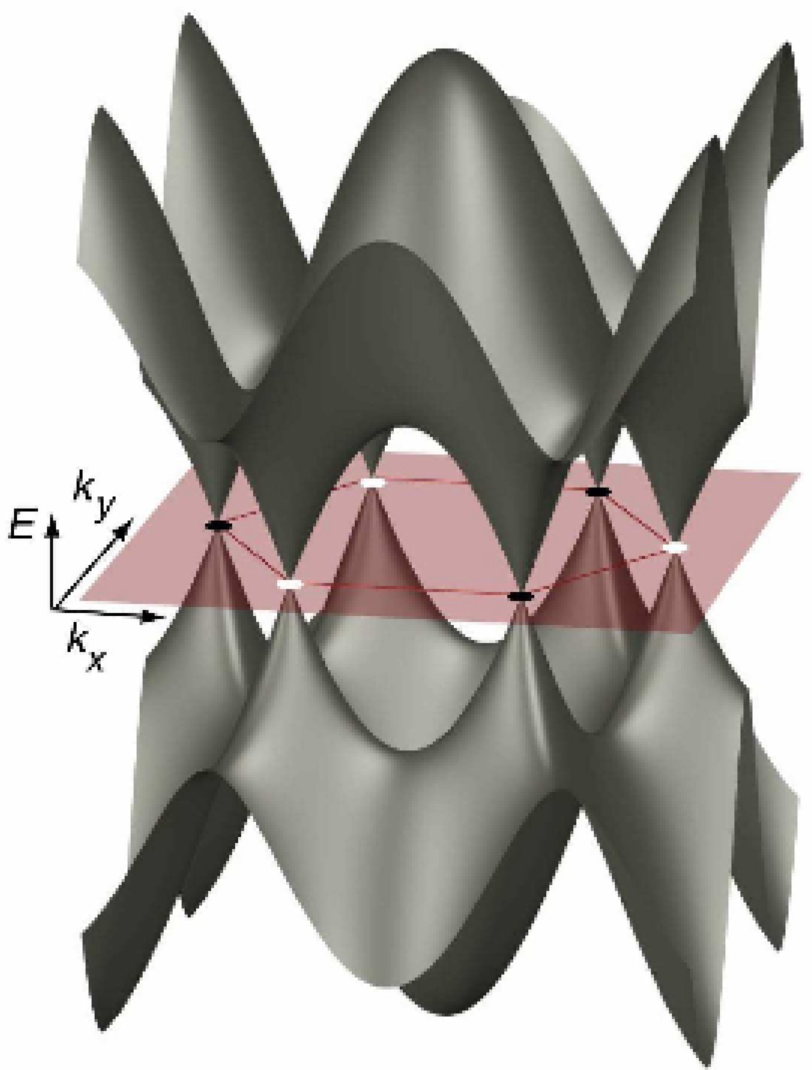
## Band structure of graphene



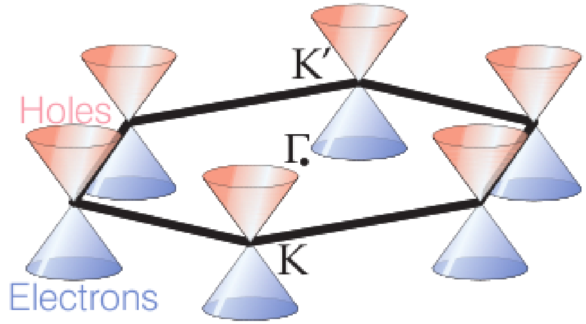
    

**Drude-Sommerfeld model of metals = Free electrons in a box + quantum mechanics + Pauli exclusion principle** results in a **Fermi Surface** and many of the properties of metals.

# Band structure of graphene

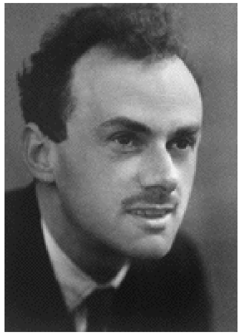


## Relativistic spectrum of massless electrons




$E(k) = \hbar v_F |\vec{k}|$

$v_F \sim 10^6 m/s \sim c/300$, good up to $\sim 1ev$

The Dirac equation 

$$\left[ i\hbar \frac{\partial}{\partial t} + i\hbar c \vec{\alpha} \cdot \vec{\nabla} + \beta m c^2 \right] \psi(t, \vec{x}) = 0$$

normally describes the quantum physics of a relativistic electron traveling at speeds comparable to light, $c = 299,792,849$ m/s.

## The Dirac equation in condensed matter

- unusual electronic properties:
  redo all of semiconductor physics with
  Schrödinger $\rightarrow$ Dirac
- explore issues in relativistic quantum mechanics which are otherwise inaccessible to experiment
- exploit the mathematical beauty of the Dirac equation

## The Dirac equation in condensed matter

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- exploit the *mathematical beauty* of the Dirac equation

**Graphene began its life as a hypothetical material**

**As a starting point for analysis of graphite**

PHYSICAL REVIEW VOLUME 71, NUMBER 9 MAY 1, 1947

# The Band Theory of Graphite

P. R. WALLACE*
*National Research Council of Canada, Chalk River Laboratory, Chalk River, Ontario*

(Received December 19, 1946)

The structure of the electronic energy bands and Brillouin zones for graphite is developed using the "tight binding" approximation. Graphite is found to be a semi-conductor with zero activation energy, i.e., there are no free electrons at zero temperature, but they are created at higher temperatures by excitation to a band contiguous to the highest one which is normally filled. The electrical conductivity is treated with assumptions about the mean free path. It is found to be about 100 times as great parallel to as across crystal planes. A large and anisotropic diamagnetic susceptibility is predicted for the conduction electrons; this is greatest for fields across the layers. The volume optical absorption is accounted for.

## 1. INTRODUCTION

THE purpose of this paper is to develop a basis for the explanation of some of the physical properties of graphite through the band

a metal. Polycrystalline graphite, on the other hand, has a much higher resistivity which varies very strongly according to the type of graphite used, and has a *positive* temperature coefficient

**As a model of emergent quantum electrodynamics in two space dimensions**

PHYSICAL REVIEW LETTERS

VOLUME 53 | 24 DECEMBER 1984 | NUMBER 26

# Condensed-Matter Simulation of a Three-Dimensional Anomaly

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(Received 4 September 1984)

A condensed-matter analog of (2+1)-dimensional electrodynamics is constructed, and the consequences of a recently discovered anomaly in such systems are discussed.

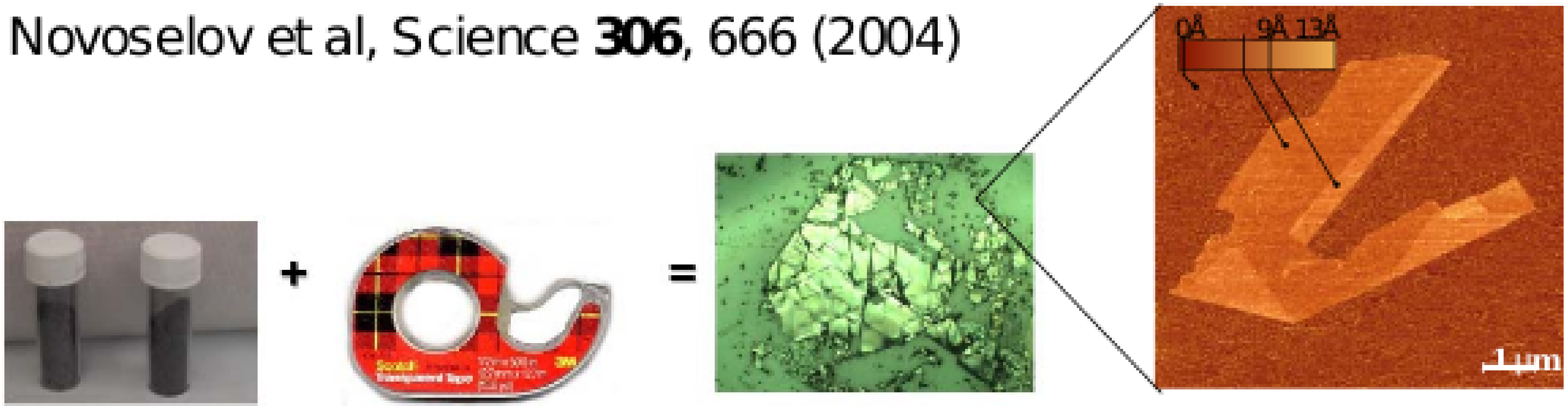
PACS numbers: 05.50.+q

Recently, new anomalous phenomena in (2+1)-dimensional systems of fermions and gauge fields have received much attention.[1–8] The associated fermion zero modes, induced currents of ab- is a general theorem that these must occur in right- and left-handed pairs.[12] In the presence of parallel external electric and magnetic fields the axial anomaly effects a transfer of electrons between the

## Graphene was produced and identified in the laboratory in 2004

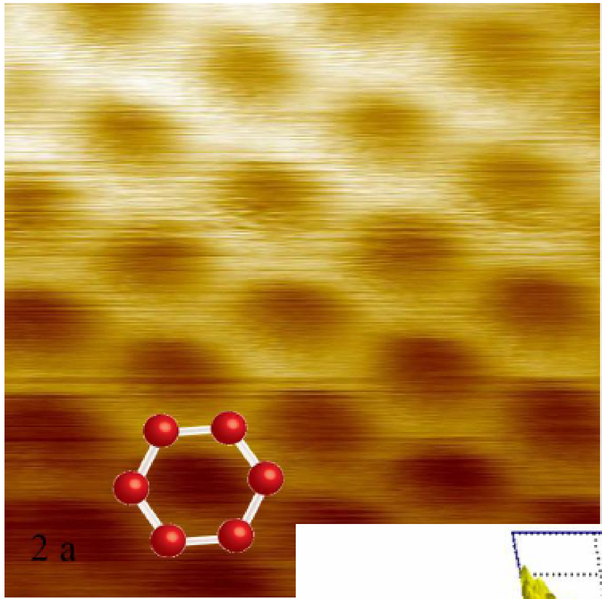
- Micromechanical cleavage of bulk graphite up to 100 micrometer in size via adhesive tapes !

Novoselov et al, Science **306**, 666 (2004)



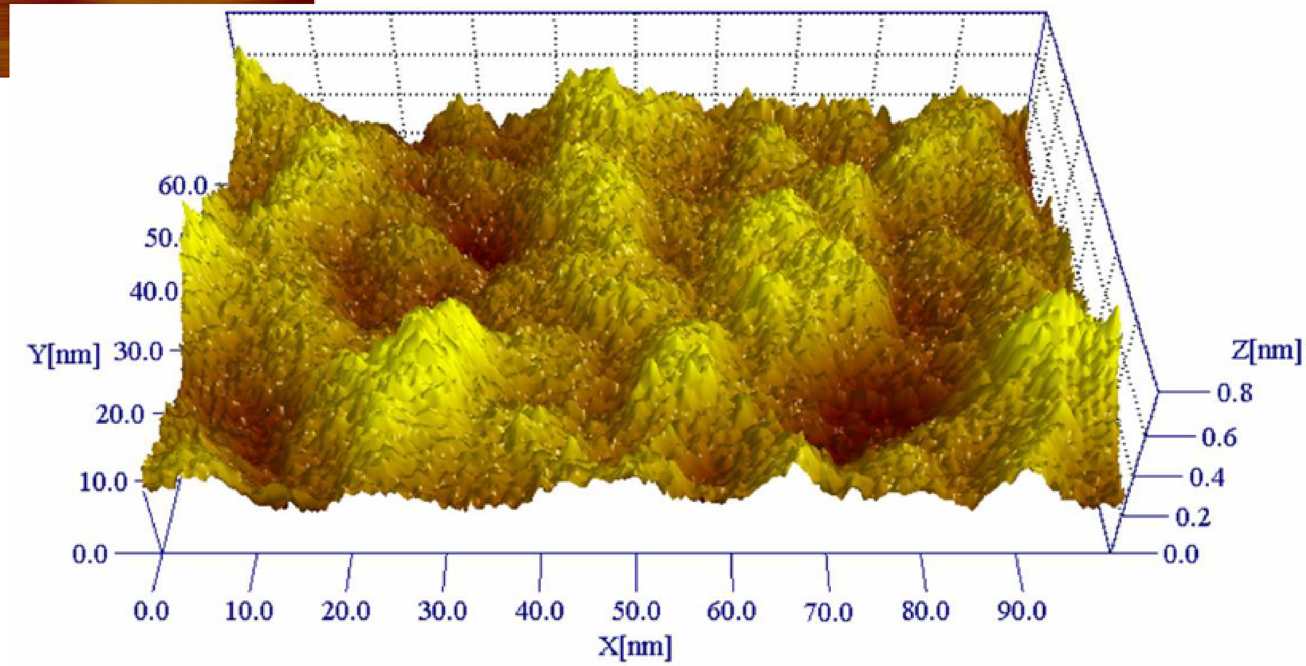

Kostya Novoselov

Andre Geim

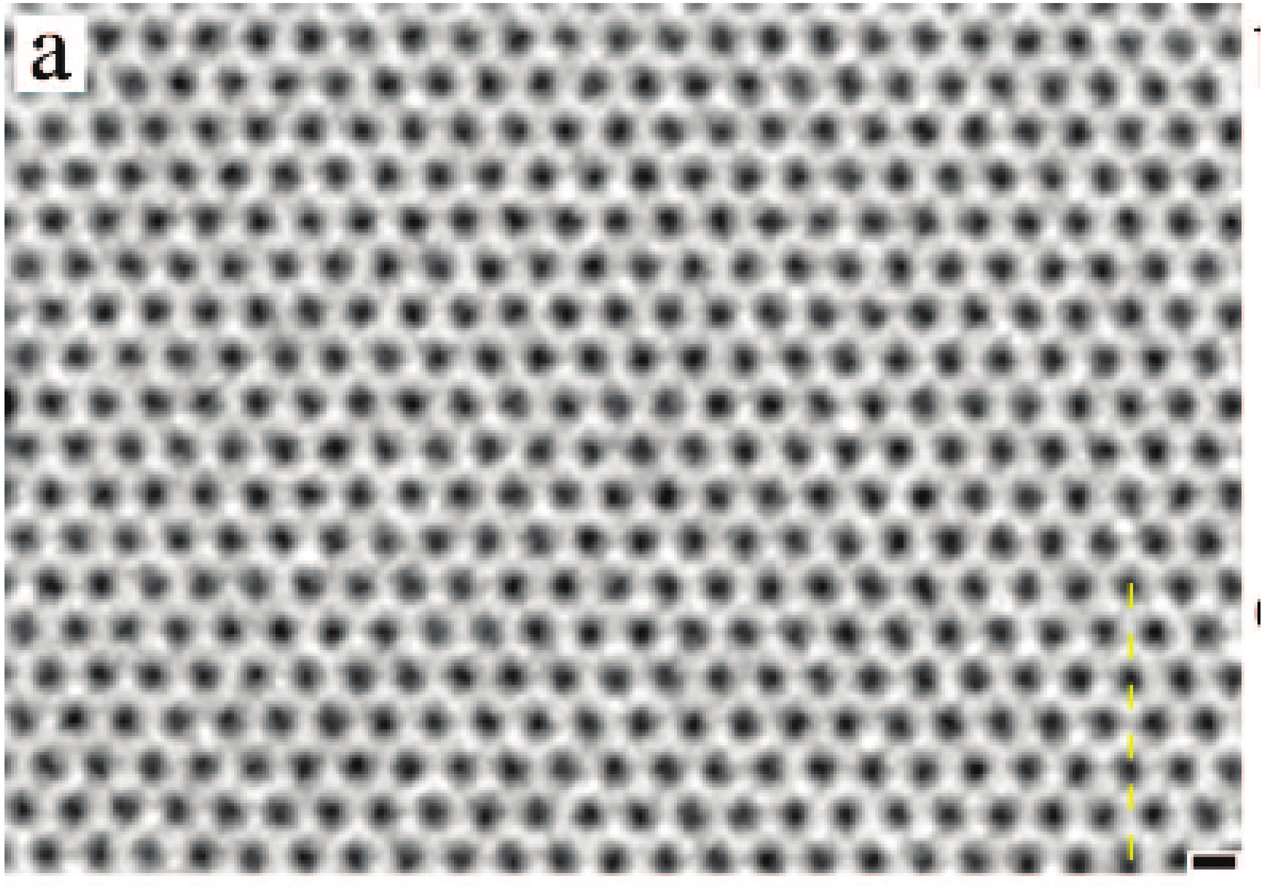



# Scanning Tunneling Microscope

E. Stolyarova et al., cond-mat/0705.0833



## TEAM Electron Microscope image




Jannik C. Meyer, C. Kisielowski, R. Erni, Marta D. Rossell, M. F. Crommie, and A. Zettl, Nano Letters 8, 3582 (2008).

## Emergent Flatland

Modeling of the fundamental world is not restricted to four dimensions

For example, string theory is in ten dimensions.

Simplified models and other examples of the complex behavior of the dynamical systems involved often involve models in other dimensions.

Circa 1975-1985 model building in particle physics revealed a number of interesting mathematical structures, some of them in quantum field theories which exist only in 2 space and one time dimension.

## Emergent Flatland

Circa 1975-1985 model building in particle physics revealed a number of interesting mathematical structures, some of them in quantum field theories which exist only in 2 space and one time dimension.

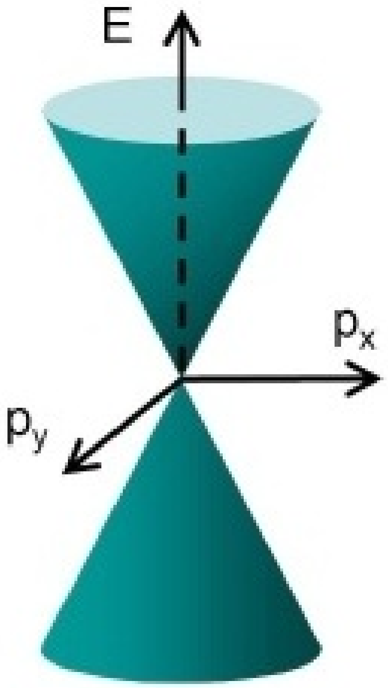
They might be relevant to modeling physics which, for some reason, occurs only in a plane.

Some "planar" physics – the quantum Hall system – was of intense interest at the time.

Field theory models were interesting because they exhibit "topological phenomena" – things that you can learn about a complex dynamical system without doing detailed calculations.

It would be a shame if nature did not make use of these ideas.

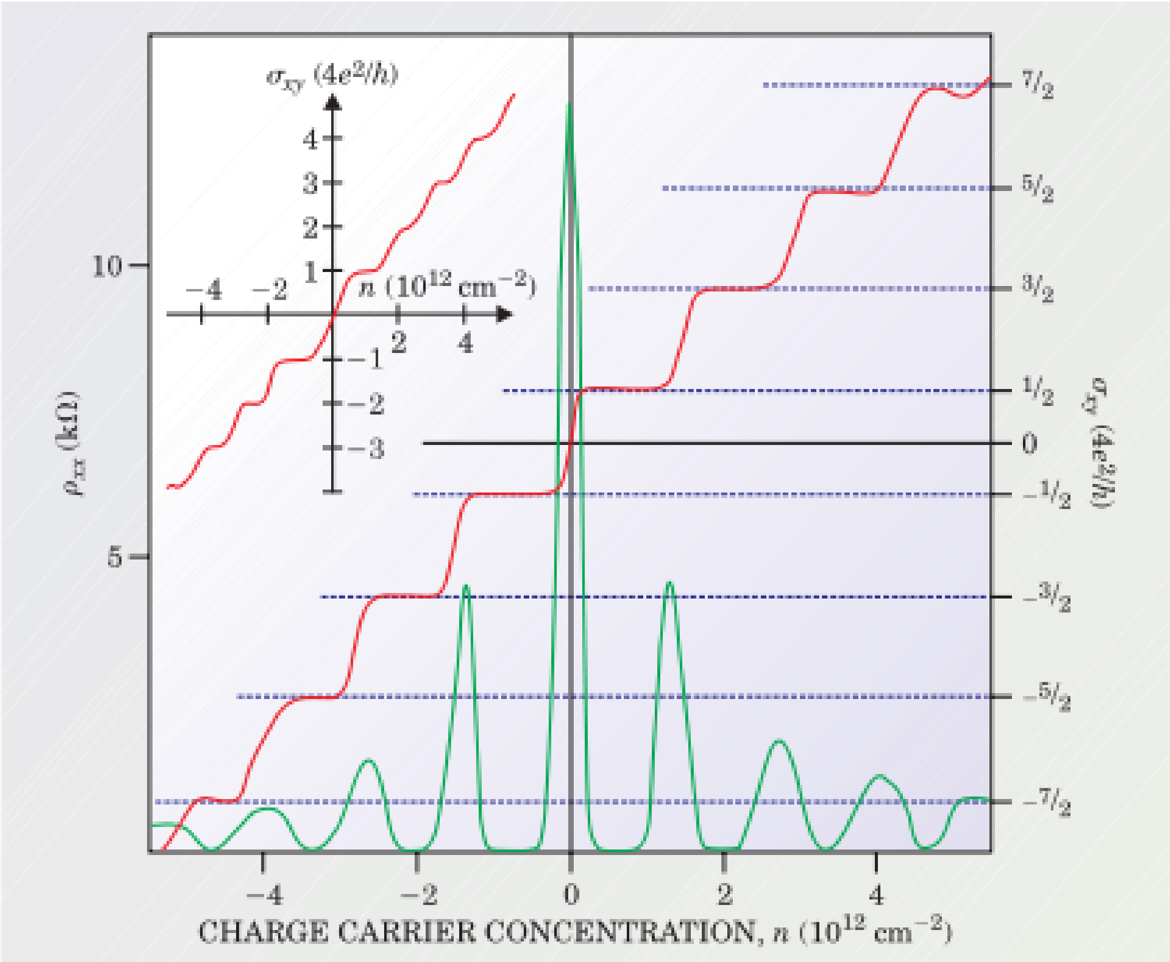
**Atiyah-Singer Index theorem** – predicts the number of quantum states of the electron at the apex of the Dirac cone.




For example, in a magnetic field,
(total number of states) $\sim$ (total magnetic flux).

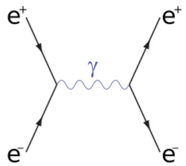
**K. Novoselov et. al.** *Nature 438, 197 (2005)*

**Y. Zhang et. al.** *Nature 438, 201 (2005)*



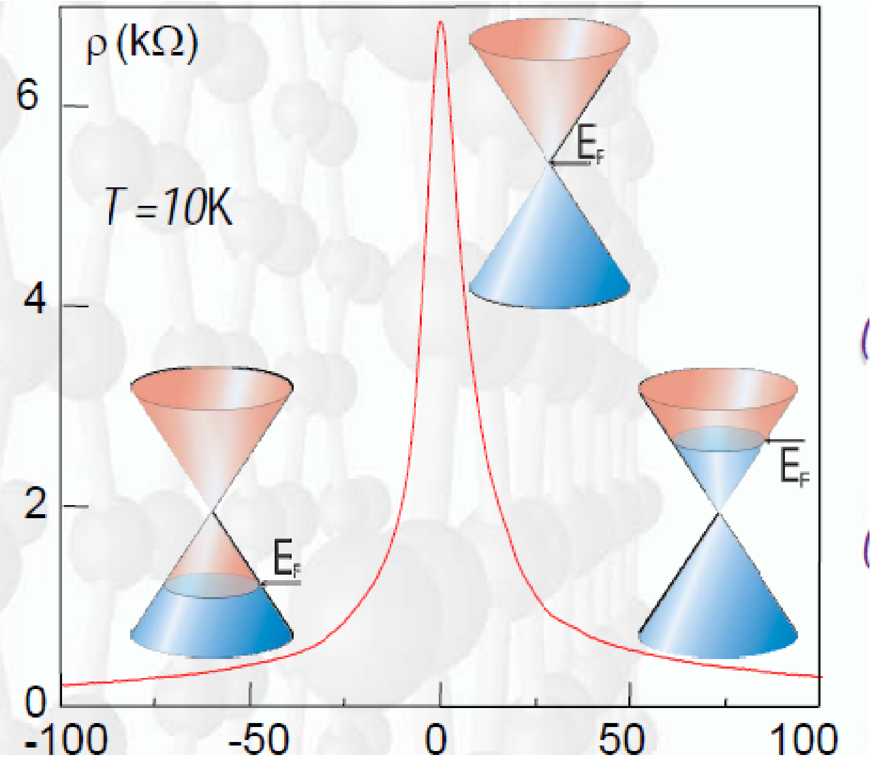

$$\sigma_{xy} = 4\frac{e^2}{h}\left(n + \frac{1}{2}\right)$$

# Relativistic Quantum Field Theory




- *"Zitterbewegung"*: "jittery" motion due to large fluctuations of velocity $\Delta v \sim c$.
- *"Klein paradox"* $\leftrightarrow$ unsuppressed quantum tunneling through barriers
- *"Schwinger effect"* – production of particle-antiparticle pairs of charged particles in and electric field
- *Supercritical* $Z > 137$ *atoms* relativistic hydrogen atom unstable if $Z$ is large enough – graphene $Z_{\rm crit} \sim 1$
- *Curved space* $\leftrightarrow$ stress, strain, corrugations
- *Dynamical issues*, *Mass condensates*, *topological effects*

*Zitterbewegung* is directly related to the fact that graphene remains a conductor even when the electron density vanishes.

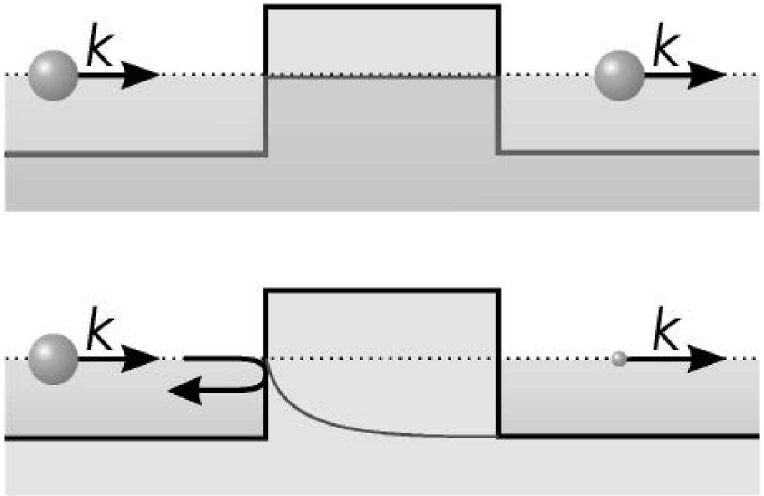


## Klein Effect

**O. Klein,** *Z. Phys. 33, 157 (1929)*

**M. Katsnelson, K. S. Novoselov and A. Geim,** *Nature Physics 2, 620 (2006)*

Unsuppressed tunneling through a potential barrier




(attempts to observe in QED in collisions of large $Z$ nuclei)

**For some applications, such as field effect transistors, it would be desirable to be able to gap the spectrum in a controllable way.**

This is related to the problem of chiral symmetry breaking in quantum field theory of the strong (nuclear) interactions.

However, the interactions between electrons in graphene seem to be too weak to drive such dynamical effects.

Dynamical chiral symmetry breaking is seen in large magnetic fields. The fractional quantum Hall effect has also been observed.

## Graphene for electronic devices

- Easy to make and manipulate, low-tech means of production
- room temp. Hall effect
- 100 GHz transistors already (IBM), speculation about terrahertz electronics
- single molecule detectors (Manchester),
- production of 30” sheets, graphene touch-screens within 3 years (Samsung)

## Physics Today, Jan. 2006

*"Microelectronics engineers are paying attention. In semiconductor heterostructures used to make FET devices for instance it takes million-dollar epitaxy machines and exquisite care to tie up dangling surface bonds and eliminate impurites in quantum wells. The preparation minimizes the scattering of electrons against interfaces and defects to ensure the largest electron mean free paths in the device.*

*But in graphene, just 1 Angstrom thick, scientists have a material that is relatively defect free and whose electrons have a respectable mean-free path naturally, without materials manipulation and processing."*

## Conclusions

- Graphene is a relativistic 2-dimensional material.
- Relativistic quantum mechanics and field theory – "the only massless Dirac particles in nature"
- Semi-conductor physics with the Dirac equation.
- Electron-electron interactions almost non-existent in native graphene AND important for Hall states, symmetry breaking and fractional Hall effect.
- Promising for electronics technology
  -low-tech means of production
  -strong, soft material, high melting temperature
  -high electron mobility, low dissipation, -room temp. Hall effect
  - 100 GHz transistor (IBM), single molecule detectors (Manchester), production of 30" sheets, graphene touch-screens within 3 years (Samsung)

# Thank You!